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Microfabrication of hybrid structure composed of rigid silicon and flexible polyimide membranes

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We have designed and microfabricated millimeter-scale wing-shaped hybrid microstructures composed of rigid structures of single crystal silicon (SCS) substrates and flexible polyimide (PI) membranes. The wing-shaped microstructures mimicking insect flapping flight have been newly designed using a fluid-structure interaction analysis, and the hybrid microstructures based on the design method have been successfully microfabricated using a simple process flow with SCS substrates coated with PI membranes. Shape of the SCS parts in the hybrid microstructures have been successfully fabricated using deep reactive ion etching (D-RIE) of the SCS substrate with small etching rate, and the wing plates of PI membranes have been prepared with the photolithography and the curing processes. The flexibility of the PI membranes of the fabricated hybrid microstructures was also confirmed using the bending test of the PI membranes.

1. Introduction: Three-dimensional microstructures of single crystal silicon (SCS) have received much attention as the key structures of bulky movable micromechanical components, and have been already used in the technical applications such as the micromechanical resonators and microcantilevers [1, 2]. The SCS offers advantages as the structural material of the movable microstructure because of the high mechanical stiffness and the low internal loss. The SCS is also convenient to create microstructure using microfabrication technologies including deep reactive ion etching (D-RIE) process of silicon. Recently, the hybrid microstructures including rigid silicon components and some flexible organic polymers also have shown much potential for some applications such as micro-robots [3] and sensing devices on a flexible substrate [4]. In the fabrication of the hybrid structures, polyimide (PI) is one of the organic polymers widely used for many electrical applications as the flexible substances [5], which is known for high thermal stability, chemical resistance, and insulation performance.

In this study, we have designed and fabricated millimeter-scale wing-shaped hybrid microstructures composed of the rigid silicon structures and the flexible PI membranes. In the microfabrication, we have proposed a fabrication process with SCS substrates and photosensitive PI, and have successfully fabricated the hybrid microstructures using D-RIE of the SCS substrates with small etching rate. Flexibility of the PI membrane part of the fabricated hybrid microstructures was also confirmed.

2. Deign of the hybrid microstructures: In this study, we have newly designed and fabricated a millimeter-scale wing-shaped hybrid microstructure, which is schematically shown in Fig. 1. This structure demonstrates the micro flexible wing mimicking insect flapping flight proposed in our previous studies [6, 7]. The present design is briefly summarized as follows:

Fig. 2 shows the concept of the micro flexible wing mimicking insect flapping flight. As shown in this figure, the so-called 2.5-dimensional structure was adopted for the micro flexible wing. In the structure, the elastic membrane is used for the wing membrane, and the stiff beam at the leading edge is used to support the elastic membrane. This wing flaps and its pitching motion is caused by the interaction with the surrounding air to create the sufficient lift [8-11]. The small input from the micro actuator is amplified to flap the wing with the large stroke angle using the resonance due to the plate spring placed at the wing base.

In this study, the substrates of SCS and PI membrane were used, respectively, for the stiff parts such as the leading edge (beam structure) and the wing base, and the flexible parts such as the wing membrane and the plate spring. Therefore, the hybrid microstructure

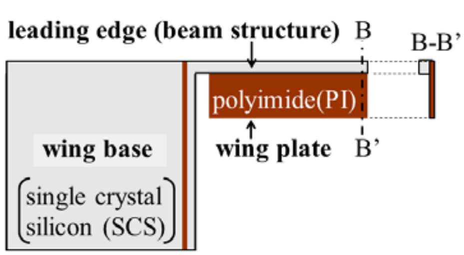

Fig. 1 *Schematic diagram of wing-shaped hybrid microstructure composed of rigid SCS and PI membranes*

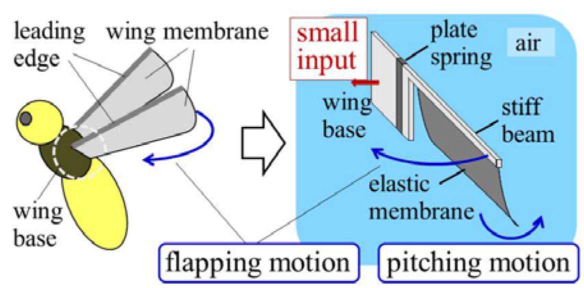

Fig. 2 *Concept for the design of micro flexible wings mimicking insect flapping flight*

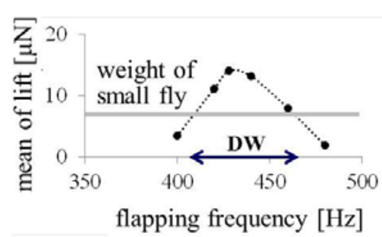

Fig. 3 *An example of the design window (DW) in the case where the wing length was set as 2.5mm*

is the fundamental structure of the micro flexible wing. The dimensions of each part of the hybrid microstructure have been determined using a fluid-structure interaction analysis [6, 7], where the equilibrium equation for the elastic body, the incompressible Navier–Stokes equations, and their interface conditions were monolithically solved using the finite element method [12, 13].

For the millimeter-scale wing length, we found the area of the satisfactory design solutions or the design window (DW) [14] in the vicinity of the resonance frequency, where each satisfactory design solution can generate the enough lift to support the weight of the actual small fly. Fig. 3 shows an example of DW in the case where the wing length was set as 2.5mm. Finally, the hybrid microstructure for the fabrication was determined based on this DW.

3. Microfabrication of the hybrid microstructures: For the microfabrication of the millimeter-scale wing-shaped hybrid microstructures shown in Fig. 1, we need to propose the methods to combine the parts of PI membrane with a rigid SCS parts of the wing (leading edge and wing base). In this study, we used spin-coating of photosensitive PI solution on the SCS substrate to combine those two materials. We used a SCS substrate of 100 µm thickness to fabricate the rigid SCS part. And, we controlled the final thickness of the PI membrane to be about 1 µm by selecting the proper rotation speed in the spin-coating.

In detail, the wing-shaped microstructures composed of SCS and PI have been microfabricated using the process flow shown in Figs. 4. At first, photosensitive PI spin-coated on the SCS substrate (Fig. 4 (a)) was patterned using photolithography process. After that, the patterned PI membranes were cured in an electric furnace at about 200˚C under low oxygen condition (Fig. 4 (b)). Then, a support substrate was temporarily bound to the upside (the side with the patterned PI membranes) of the SCS substrate (Fig. 4 (c)). And, photosensitive resist (photoresist) spin-coated on the backside of the SCS substrate was patterned using photolithography process to prepare the protection mask pattern for the D-RIE process of the SCS substrate (Figs. 4 (d), (e)). After the D-RIE process of the SCS substrate (Fig. 4 (f)), the residual photoresist pattern was removed (Fig. 4 (g)). And finally, the wing-shaped hybrid microstructures were released from the support substrate which had been temporarily bonded in step (c) (Fig. 4 (h)). In the microfabrication process, the D-RIE process was so important step to fabricate the rigid microstructures combined with thin flexible PI membranes. Therefore, we had investigated proper process conditions in the D-RIE process (Fig. 4 (f)), and used the process condition with so small etching rate of SCS (about 1.1 µm/min) to prevent the break of the PI membranes.

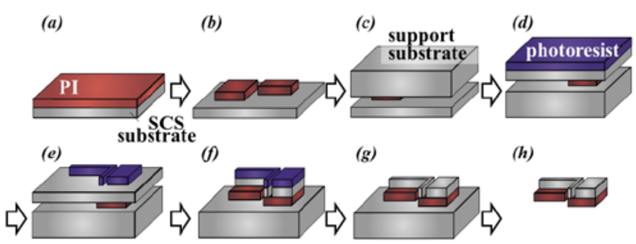

Fig. 4 *Process flow of the wing-shaped hybrid microstructure:*
(a) spin-coating of photosentive polyimide (PI) on a SCS substrate, *(b)* photolithography and curing of patterned PI membranes, *(c)* bonding of a supporting substrate on the side of PI patterns of the SCS substrate, *(d)* spin-coating of photoresist on the backside of the SCS substrate, *(e)* photolithography of photoresist, *(f)* D-RIE through the SCS substrate with photoresist mask patterns from the backside, *(g)* removal of residue of the photoresist patterns, and *(h)* release of wing-shaped hybrid microstructure from the supporting substrate.

Fig. 5 shows photos of the wing-shaped hybrid microstructures fabricated on the support substrate by the controlled D-RIE process condition. After that, we have successfully fabricated wing-shaped hybrid microstructures as shown in Figs. 6 by releasing them from the support substrate.

4. Flexibility measurement of the fabricated PI membrane: In the fabrication of the hybrid microstructure of this study, it is also required to prepare the wing plate of flexible PI membranes. Therefore, we also have investigated the flexibility of the PI membrane of the fabricated microstructures. In detail, we have added load to the PI membrane (wing plate) of a fabricated hybrid microstructure to confirm the flexibility of the PI membrane. Figs. 7 show the results of an experiment, in which a PI membrane was deformed by adding load with the moving probe. (bending test). The PI membrane was deformed when the load was added to the membrane by the probe (Fig. 7 (a)), and the PI membrane kept the deformed condition while the load was added (Fig. 7 (b)). However the PI membrane returned to the original shape when the added load

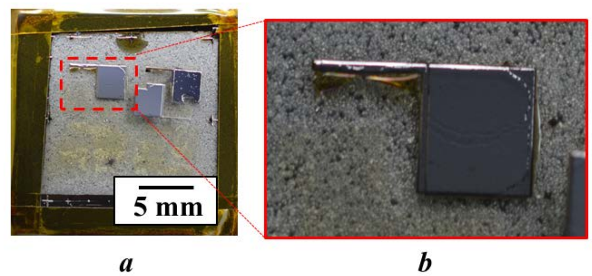

Fig. 5 *Photos of wing-shaped hybrid microstructures fabricated on the support substrate after the D-RIE process*
a Three microstructures on the support substrate
b Magnified image of one of the microstructure

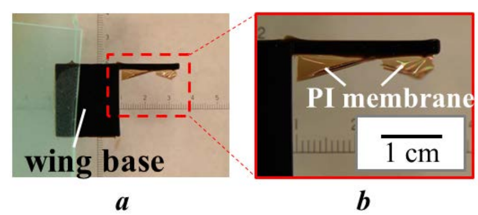

Fig. 6 *Photos of a released wing-shaped hybrid microstructure*
a Whole structures of the microstructure.
b Magnified image around the polyimide (PI) membrane

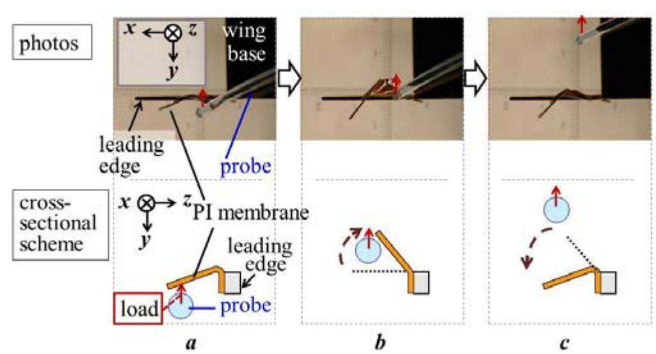

Fig. 7 *Flexibility measurement of PI membrane of the fabricated wing-shaped hybrid microstructure:*
a step-1: load was added to PI membrane from the probe,
b step-2: PI membrane deformed by added load,
c step-3: PI membrane returned to the original shape when the load had been removed.

had been removed (Fig. 7 (c)). The flexibility of the PI membranes of the fabricated microstructure was confirmed using the bending test of the PI membrane.

4. Conclusion: In conclusion, we have designed and microfabricated millimeter-scale wing-shaped hybrid microstructures composed of rigid SCS structures and flexible PI membranes. In the microfabrication, we have proposed a simple process flow with SCS substrates coated with PI membranes. Shape of the SCS parts in the hybrid microstructures have been successfully fabricated using deep reactive ion etching (D-RIE) of the SCS substrate with small etching rate, and the wing plates of PI membranes have been prepared with the photolithography and the curing processes. The flexibility of the PI membranes of the fabricated hybrid microstructures was also confirmed using the bending test of the PI membranes.

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